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Localised human thermal discomfort assessment using high temporal resolution meteorological data: A case of University of Zimbabwe

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ABSTRACT

This study investigated the thermal discomfort patterns at the University of Zimbabwe in Harare, Zimbabwe; paying attention to the outdoor and indoor seasonal and diurnal variations. Temperature and relative humidity data from an automatic weather station located in the study area was incorporated into the temperature humidity index to retrieve outdoor human thermal discomfort patterns. Based on data availability, air temperature and humidity hourly data for the period 2014 to 2018 was used. The indoor human thermal discomfort patterns were then obtained using the linear relationship between outdoor temperatures and indoor comfort. The results show that there were only an average of 31 days per year of indoor thermal discomfort days in the hot and rainy seasons. There were on average 303 days in which at least half of the subjects felt thermally comfortable outdoors yearly. Throughout the whole year there were no heat stresses, 62 days of cold stress outdoors, and 334 days of cold stress indoors. The hot season was found to be the most thermally comfortable with 25% and 33% of thermally comfortable hours per day indoors and outdoors, respectively. It was concluded that subjects were mostly comfortable in the afternoon both indoors and outdoors. The study recommended that as more data is collected, future researchers should consider a longer period for analysis. The findings of this study are important for understanding, modelling and monitoring human thermal comfort/discomfort at learning institutions, work places and other environments. Such information can be used for making building guidelines on including systems like air conditioning units in response to climate change and increased variability.

1. Introduction

Thermal discomfort has many impacts on different sectors such as the energy sector and health sector. Comfort is established as a result of the interaction of physical, physiological, psychological, and social exchange. It depends on architecture, clothing, eating habits and the climate (Gagge and Fanger, 2015). Major diseases associated with heat and nature of the thermal environment include hyperthermia, heat rash (prickly heat), heat cramps, heat oedema (swelling), hyperventilation, heat stress, heat syncope and heat exhaustion (Mozaffarieh et al., 2010; Ormandy and Ezratty, 2016; Smith et al., 2014). These adverse impacts have also been greatly enhanced by climate change due to variations in temperature extremes at a global scale (Matzarakis et al., 2008; Thorsson et al., 2011; Wilson et al., 2008). The Intergovernmental Panel on Climate Change (IPCC) concluded in a special report for extreme events (SREX) that there has been an overall decrease in the number of cold days and nights, and an overall increase in number of warm days and nights (Smith et al., 2014). It follows that the number of heat related deaths has also increased, with a decline in deaths associated with cold spells (Potchter and Ben-Shalom, 2013). However, the impact on health of more frequent heat extremes outweigh benefits of fewer cold days (Kinney et al., 2015). Additional work, therefore, needs to be done so as to minimize and provide solutions to related adverse effects especially on human health.

In order to achieve an acceptable thermally comfortable environment, many factors are considered which include air temperature, relative humidity and mean air velocity (Turner et al., 2013). Different thermal indices have been developed, some of which based on generalized results of measurements, while others are based on observed reactions of the human body to different thermal conditions (Blazejczyk et al., 2012; D'Ambrosio et al., 2013; Holopainen et al., 2014; Urban and Kyselý, 2014) Most indices illustrate the integrated effect of individual meteorological variables on humans, some being based on empirical research and some on theoretical deliberations (Blazejczyk

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et al., 2012). A large number of models, relative to area of interest, attempt to describe thermal comfort (Almeida, 2010; Bouden and Ghrab, 2005; Charles, 2003; Nguyen et al., 2012; Roelofsen, 2016). In general, these indices estimate balance between different factors related to thermal properties of an area, coming up with ranges of values at which balance is restored. As temperatures are related to land use and land cover spatial structure which vary from place to place, area specific assessments need to be done especially in places such as universities which host large groups of people at any given time.

Analysis of meteorological data is necessary in obtaining thermal properties of an area. Surface weather observations are widely expanding due to availability of new technologies, enhanced data transmission features and transition from manual to automatic equipment. Manual instruments are widely used in developing countries with the major disadvantage being limited frequency of observations. In most cases the observations are taken at widely spaced synoptic stations and observation times as recommended by the World Meteorological Organisation (WMO). High temporal resolution at frequencies accustomed to user demands can be obtained using Automatic Weather Stations (AWS). An AWS automatically records observations from measuring instruments converting measurements of meteorological elements into electrical signals through sensors. The station further process and transform these signals into meteorological data, and transmit the resulting information by wire or radio or automatically storing it on a recording medium (KNMI, 2000). The advantageous characteristic of frequent observations makes the use of AWS plausible, hence the need for use in thermal discomfort assessments. It is quite not often to find such high resolution data in resource constrained nations thus important to fully utilize the resource when available.

Studies on urban thermal conditions were mostly done in Europe, Asia and North America; most of them appreciating the urban heat islands concept due to the rapid urbanisation in these countries (Akbari et al., 2001; Feriadi and Wong, 2004; Keramitsoglou et al., 2011; Nguyen et al., 2012; Ren et al., 2012; Widyasamratri et al., 2013; Yang et al., 2013). Very little work has been done in Africa, with work done in Zimbabwe centralising on Harare and failing to shrink focus to more localised scales (Mushore et al., 2018). Mushore et al. (2018) relied heavily on Landsat 8 data whose temporal resolution is course and may not adequately represent temperatures on the ground. There is thus need to monitor human thermal discomfort patterns especially for environments such as learning institutions and work places in Africa where large numbers of occupants could be at risk of extremes. In Zimbabwe specifically, large numbers of people are investing in education implying the need to ensure that they are all comfortable with their thermal environments. Evidently, there is need to assess localised temporal variations in human thermal discomfort in- and outdoors in order to formulate informed response strategies.

Thermal sensation and comfort are bipolar phenomena which range from uncomfortably cold (cold stress) to uncomfortably warm or hot (heat stress) with comfort or neutral sensations being somewhere in between (Parsons, 2003). Studies of thermal sensation have used scales to quantify the psychological response of a group of subjects in response to thermal environment conditions. While many studies have analysed thermal discomforts at city and landscape scale (Ca et al., 1998; Chang et al., 2007; Chen and Wong, 2006; Emmanuel, 2005; Potchter and Ben-Shalom, 2013; Puliafito et al., 2013; Ruiz and Correa, 2014; Weng and Yang, 2004; Yilmaz et al., 2007), studies concentrating on much localised scenarios such as those at learning institutions specifically have remained scarce. Considering large populations at learning facilities and the obligation of any learning facility to ensure a safe and comfortable environment, thermal studies are of great importance. According to an experimental evaluation of the influence of thermal discomfort on the attention index of students (Mazon, 2014), attention level is sensitive to discomfort conditions, decreasing around 50% in discomfort conditions with respect to comfort conditions for those aged 12–14 years. Need therefore arises, to monitor the thermal processes of the learning institution which in turn affect overall performance of both students and lecturers.

The objectives of the study was thus to assess temporal variations in in- and outdoor human thermal discomfort patterns using high temporal resolution meteorological data. A case of the University of Zimbabwe (the oldest in the country) was studied.

1.1. Brief review of literature on thermal discomfort analysis methods

1.1.1. Outdoor thermal discomfort analysis

The wet-bulb globe temperature index (WBGT) is the most widely used index throughout the world. It employs the dry-bulb temperature (Ta), wet-bulb temperature (Tw) and black-globe temperature (Tg) in the following manner (Ahmed et al., 2014; D'Ambrosio et al., 2013; Okamura et al., 2014; Vernon and Warner, 1932; Yaglou and Minaed, 1957):

$$\text{WBGT} = 0.7\ \text{Tw} + 0.1\ \text{Ta} + 0.2\ \text{Tg} \tag{1}$$

This index is recommended by many international organisations and was adopted as an ISO standard (ISO 7243) (Parsons, 2006). Okamura et al. (2014) linked WBGT with socio-economic activities in different parts of the world and observed high wet WBGT in countries with low Gross Domestic Product (GDP) per capita. Yaglou and Minaed (1957) observed high correlation between WBGP and evaporative sweat when investigating the total heat stress imposed on men in military training due to physical training, humidity, radiation and wind in the United States. The most influential limitation of the WBGT in its application is the inconvenience of measuring the black-globe temperature (Tg). It is measured by a temperature sensor placed in the centre of a thin copper matt-black globe (diameter of 150 mm); which is cumbersome and impractical in many circumstances (Francisco, 2001). WBGT can only be used for rough evaluation of heat stress not for a high metabolic rate (d'Ambrosio et al., 2004). In order to counter these limitations, another index called the discomfort index (DI) has been implemented in thermal discomfort studies and calculations. It was originally proposed by Thom (1959) and later on modified to be expressed by a linear equation based on dry-bulb (Td) and wet-bulb (Tw) temperatures in the following manner:

$$\text{DI}\ (^{\circ}\text{F}) = 0.4\ (\text{Ta} + \text{Tw}) + 15 \tag{2}$$

According to Polydoros and Cartalis, if air temperature (Ta) is measured and relative humidity is given, DI can be calculated using the Temperature humidity index, expressed as (Polydoros and Cartalis, 2015):

$$\text{DI}\ (^{\circ}\text{C}) = \text{Ta} - 0.55(1 - 0.01\ \text{RH})\ (\text{Ta} - 14.5) \tag{3}$$

It is a measure of apparent temperature caused by effects of temperature and relative humidity; emphasizing the importance of relative humidity in determining thermal comfort. The DI in this form was applied and found to be satisfactory when it was used for Harare (Mushore et al., 2018). Based on DI, Tawhida et al., (2013) observed that 100% of the population of Khatoum experience heat stress in the hot season. In Mossoro Brazil, DI analysis showed uncomfortable conditions in the wet season which were attributed to low wind speeds (Azevedo et al., 2015). Polydoros and Cartalis (2014) used the DI in Athens to show that effects of a heat wave were more severe in places with dense buildings than in sparsely built, dense vegetation and mountainous area. Another commonly used temperature-humidity index (THI) was developed by Thom (Om, 2015). It provides an approximation of stress changes in a city over time, specifically for developing design guidelines for cities (Jauregui, 1993). The THI is another discomfort index which combined wet and dry bulb temperatures was then modified so it could use air temperature and relative humidity as shown in the following expression (McGregor and Nieuwolt, 1998; Polydoros and Cartalis, 2015):

Table 1
THI comforts classes and interpretation (Polydoros and Cartalis, 2015).

THI Scale	Comfort conditions.
THI < 15	100% of subjects feel uncomfortable due to cold stress.
15 < THI < 21 °C	50% of subjects feel comfortable, and 50% under cold stress.
21 < THI < 24 °C	100% of subjects feel comfortable.
24 < THI < 26 °C	50% of subjects feel comfortable, and 50% under heat stress.
THI > 26 °C	100% of subjects feel uncomfortable due to heat stress.

$$THI = 0.8T + (HT/500) \tag{4}$$

Where THI is the temperature-humidity index, T is the air temperature (°C) and H is the relative humidity (%). The classification is as shown in Table 1:

The THI was used in a case study for examining the thermal comfort and responses to physiological stress in Nigeria (Om, 2015). The study concluded that thermal stress will increase in many parts of Nigeria due to increasing rate of urbanisation, population and the global temperature increase. In a study on long-term changes in thermal comfort in Sri Lanka Emmanuel (2005) concluded that tropical residents are likely to tolerate high THI levels due to variations in food, habits and clothing. The other advantage with this index is that it considers both heat stress and cold stress regions, thereby fully exhausting the thermal conditions experienced at any learning institutions. WBGT requires three variable thus is less parsimonious than DI and THI which require only two. The use of either DI or THI to assess outdoor thermal discomfort puts less strain on data scarce nations and should be encouraged. However, it is important to acknowledge the limitation that these simple indices, unlike Physiological Equivalent Temperature (PET) and Predicted Mean Vote (PMV), consider only climatic parameters and ignore human physiology.

1.1.2. *Indoor thermal discomfort analysis*

Humphreys (2008) related the indoor comfort temperatures to outdoor mean temperatures, differentiating between comfort in free-running buildings (naturally ventilated) and those which are heated and cooled. Basing from his work, Humphreys and Nicol (2008) suggested an algorithm to determine the indoor comfort temperatures in relation to the outdoor temperatures, concluding that the comfort temperature (Tc) in free running buildings depends on the outdoor temperature (To) as represented by equation (5) (Baskar, 2015):

$$Tc = 11.9 + 0.534To \tag{5}$$

A study on indoor temperature and comfort temperatures by Baskar (2015) confined thermal comfort to be between 26 °C and 32.5 °C. As for comfort conditions in heated or cooled buildings it is a matter of custom, and as long as the change in conditions is sufficiently slow people can adapt (Humphreys, 1978; Nicol and Humphreys, 1986). The indoor comfort temperatures will change with seasons, respective to the natural change in ranges of temperature associated with the different seasons. In this case, only the outdoor temperature is used to determine comfort conditions, but comfort is clearly a function of many other factors, like the contribution of clothing and insulation respective to the season people are in (Nin, 1999). Humphreys (1978) stressed that the relationship between outdoor temperature and indoor comfort help in designing of builings and in their economical operation. Overall, comfort indices retrieved from meteorological data provide easy to use, parsimonious and efficient techniques for monitoring indoor and outdoor thermal comfort.

2. Materials and methods

2.1. *Description of study area*

The study was conducted at the University of Zimbabwe (UZ), the oldest tertiary education facility in Zimbabwe with a large population size of about 21 000 including members of staff and students (www.uz.a.zw). Over the past years, the institution has been experiencing growth in both population and built up area. Lecture rooms and learning facilities occupy the largest area of the site mainly to the east and south, sporting fields and facilities to the south-west and halls of residence to the north-east. The university is within a low density residential Mount Pleasant suburbs. In Harare low density residential areas occupy the northern and north-eastern parts of Harare with plot sizes of about 1000 m^2 (Gamanya et al., 2009; Mbiba, 1994). Harare is located in the Highveld of Zimbabwe with higher altitude in the northern and north-eastern parts where the university is situated (Kamusoko et al., 2013; Mvungi et al., 2003). The mean annual rainfall for Harare is 800 mm while the average temperature ranges between 18 and 20 °C in a sub-tropical climate (Mbiba, 1994; Mvungi et al., 2003). Harare experiences a warm wet season from mid-November to April, a cool season from May to August and a hot mid-September to mid-November (Kamusoko et al., 2013). Daily temperature ranges from about 7 to 20 °C in July (the coldest) and 13–28 °C in October – the hottest (Kamusoko et al., 2013). Despite the incessant efforts by the institution's board to cater for the needs of the staff and students as well as improve their overall concentration, precise documentation on thermal properties which is an important insight on possible strategies to be implemented for the area lacks.

2.2. *Pre-processing of weather data*

Field data was obtained from an automatic weather station in the Physics Department at UZ. The database holds weather data from the year 2014 to date. The data was subdivided, by taking averages of the three years from 2014 to 2017 to come up with four sets of separate maximum temperatures, minimum temperatures and relative humidity data catering for the hot season (mid-September to mid-November), the rainy season (mid-November to mid-March), the post-rain season (mid-March to mid-May), and the cool season (mid-May to mid-September) for use in determining seasonal thermal comfort variations for the study area. Given that the automatic weather station is located on the roof a correction was required to estimate surface temperatures. The height of the building was factored together with the lapse rate of 9.8 °C to estimate air temperature at a height of 2 m above the ground. In order to enable further analysis the temperature and humidity data were sorted into the following categories

- Raw hourly data running from the first hour of 2014 to the last hour of 2017
- Mean hourly (average for each hour computed over the four year period)
- Daily average computed from mean hourly data over the four years
- Daily minimum and maximum

2.3. *Annual variation of average diurnal outdoor and indoor thermal comfort*

For outdoor thermal comfort, equation (4) was used, which relates the THI to temperature and humidity. The daily averages of the temperature and relative humidity were related to THI, and the variation of THI against time (in days) was plotted. For the indoor thermal comfort variation, a plot of Tc against time in days was obtained after deriving Tc from the mean outdoor temperatures using equation (5).

2.4. Variation of average monthly indoor and outdoor thermal comfort patterns

Using the THI comfort classes stated in Table 1, the daily averages THI values were grouped into their corresponding THI value classes, and then expressed as a percentage of the total number of days in that month. A graph relating the percentage variation of the THI comfort classes to their relevant months was plotted. In order to understand variations in mean indoor comfort, the same procedure was done for Tc, using 26 °C and 32.5 °C as the lower limit and upper limit respectively.

2.5. Diurnal variation of average seasonal indoor and outdoor thermal comfort patterns

Using hourly averages of temperatures and relative humidity data, THI and Tc values were calculated for the whole period. The THI and Tc values were then grouped into seasonal classes in the following criteria; rainy season, post rainy season, cool season and hot season. In the end, hourly averages of diurnal variations of THI and Tc for each season were obtained. These were then plotted against time in hours to obtain diurnal variations of THI and Tc for each season.

2.6. Outdoor comfort conditions for observed temperature and relative humidity variations

From the relative humidity and temperature data used, the highest and lowest values for each variable were obtained. Using the classification of thermal variation in Table 1, the ranges of maxima and minima for comfort THI values for at least 50% of subjects were obtained (24 and 15 respectively). Variation of the comforts fixed at 24 °C and 15 °C in turn were plotted by relating the range of values of relative humidity corresponding to UZ against the range of values of average temperature in conjunction with the temperature-humidity index (equation (3)). In this way, boundaries corresponding to outdoor comfort in relation to temperature and relative humidity were obtained.

3. Results

3.1. Average monthly temperature and humidity

The 3-year (2016–2018) average maximum, minimum and mean temperatures for the University of Zimbabwe were found to range between 29.53 °C and 21 °C, 16.86 °C and 9.14 °C, and between 22.93 °C and 15.07 °C, respectively. The variations in temperatures were highest between August and October, with an average margin of 13 °C. The lowest recorded minimum temperatures were in July (cool season), with the highest maximum temperatures recorded in October (hot season). The average maximum, minimum and mean relative humidity, were ranging between the highest maximum recorded of 90.66% in February (rain season) and the lowest minimum recorded of 16.16% in September (hot season).

3.2. Average monthly THI values and their associated discomfort levels

The outdoor thermal comfort index (THI) was highest in October (hot season) and the lowest in July (cool season). The indoor comfort (Tc) was highest in October, and lowest in July (cool season) (Table 2). On average, based on THI partial comfort (50% of the population would feel comfortable) was recorded outdoors for most months of the year, whilst during the cool season (June and July), the population was under cold stress. It was rarely 100% comfortable (everyone would feel comfortable) outdoors at the University of Zimbabwe. During the hot season (mid-September to mid-November) 50% of the students would feel uncomfortable outdoors. However, the hot period of the year is the most comfortable indoors at the University of Zimbabwe. During the other times of the year, indoor temperatures are low causing cold stress to the subjects.

Table 2
Average monthly THI and Tc values and their associated discomfort levels.

Month	Outdoor discomfort		Indoor discomfort	
	Average THI	THI Level	Average Tc	Tc Level
January	19.64	50% comfort*	24.93	Cold stress
February	19.97	50% comfort*	24.99	Cold stress
March	19.33	50% comfort*	24.72	Cold stress
April	17.38	50% comfort*	23.62	Cold stress
May	16.30	50% comfort*	23.09	Cold stress
June	14.27	Cold stress	21.98	Cold stress
July	13.62	Cold stress	21.64	Cold stress
August	15.17	50% comfort**	22.71	Cold stress
September	17.87	50% comfort**	24.50	Cold stress
October	20.22	50% comfort**	25.88	Comfortable
November	20.09	50% comfort**	25.52	Comfortable
December	20.07	50% comfort**	25.24	Cold stress

comfort* - due to low temperatures, comfort**- condition.

3.3. Trends in temperature, relative humidity and outdoor thermal comfort at UZ

The annual temperature, relative humidity and THI trends are shown in Fig. 1. The biggest fraction of THI daily average values are in the range 15 < THI < 21 (50% feel comfortable), followed by cold stress, and then comfort conditions with the least number of occurrences. There are no heat stresses throughout the whole year. Cold stresses lying between days 115 and 255 were experienced and corresponded to the cool season. As for the temperatures, they were highest between days 290 and 300 (hot season) of the year and lowest between days 150 and 210 (cool season). The relative humidity ranged from 6% up to 92%. The hot season was characterised by high temperatures and low relative humidity while the cool season was characterised by both low temperature and relative humidity. Outdoor thermal comfort decreased with both temperature and relative humidity in the cool and post rain seasons (day 1 to day 190). Changes in pattern were recorded in the hot and rainy seasons where outdoor discomfort increased with air temperature and inversely related with relative humidity (day 190 to day 365).

3.4. Trends in outdoor temperature and indoor thermal comfort

According to Fig. 2, the closer the outdoor temperatures are to 26 °C, the closer they will be to Tc. The majority of days fell under the comfort levels (Tc < 26) with a few days between days 260 and 340 (hot and rain seasons) of the year in comfort conditions. The daily averages of outdoor temperatures ranges between 13 °C and 27 °C, and Tc between 20 °C and 28 °C. While the Tc values were below the lower limit for indoor comfort, they were lower in the cool season than other season. In winter they dropped significantly approaching the cold stress extreme.

3.5. Average occurrence of outdoor comfort days in each month

Table 3 shows the total number of days in each month and their respective discomfort conditions. In the period 2016 to 2018, there were no days with heat stress conditions (26 < THI < 24), with only 25 days in which 100% of students felt comfortable with the outdoor conditions. The majority of the days were in the range 15 < THI < 21 (50% of subjects feel comfortable), with only 62 days of cold stress on average throughout the whole year.

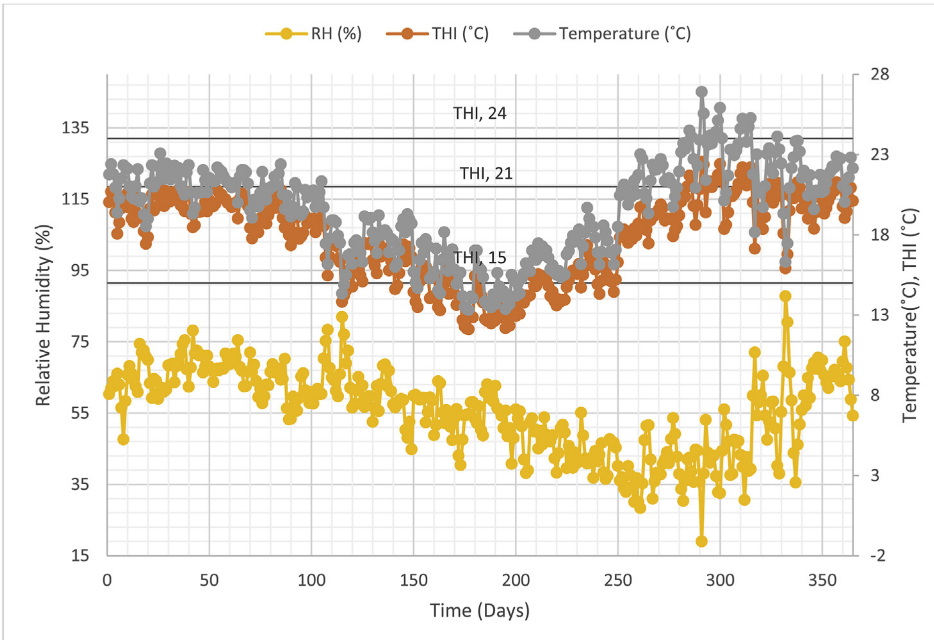

Fig. 1. Average annual patterns of outdoor thermal discomfort at UZ.

3.5.1. Percentage frequency of occurrence of outdoor comfort conditions per day in each month

The results in Fig. 3 were analysed to obtain the percentage frequency of occurrence of discomfort conditions with respect to days in each month in a year. The highest frequency of occurrence of outdoor comfortable days is in October (35%) as shown in Fig. 3, the lowest being 3% in January. February and March had 100% occurrence of conditions in which 50% of the subjects felt comfortable in a day. July has the highest percentage of days under cold stress, at 93.5%.

3.6. Average occurrence of indoor comfort days in each month

According to Table 4, none of the days per year were under heat stress conditions indoors. The majority of the days were under cold stress, with only 31 comfortable days throughout the whole year in October, November and December.

3.6.1. Frequency of occurrence of indoor comfort conditions per day in each month

As analysed in Fig. 4, the months January to September had 100% occurrence of cold stress. The highest frequency of occurrence of comfort conditions were in October (52%), with the lowest in December at 10% frequency of occurrence per month.

3.7. Average diurnal variation of seasonal outdoor thermal comfort

All diurnal variations of outdoor thermal comfort for the seasons have a minimum between 6 a.m. and 8am, and a maximum at around 3pm, and no heat stress conditions throughout the whole day as shown in Fig. 5. The cool season outdoor diurnal variations range between 10 °C and 19 °C, post-rain between 13 °C and 21 °C, rainy between 16 °C and 22 °C, and the hot season between 15 °C and 24 °C. In the cool season, cold stress was experienced in both the morning and night time.

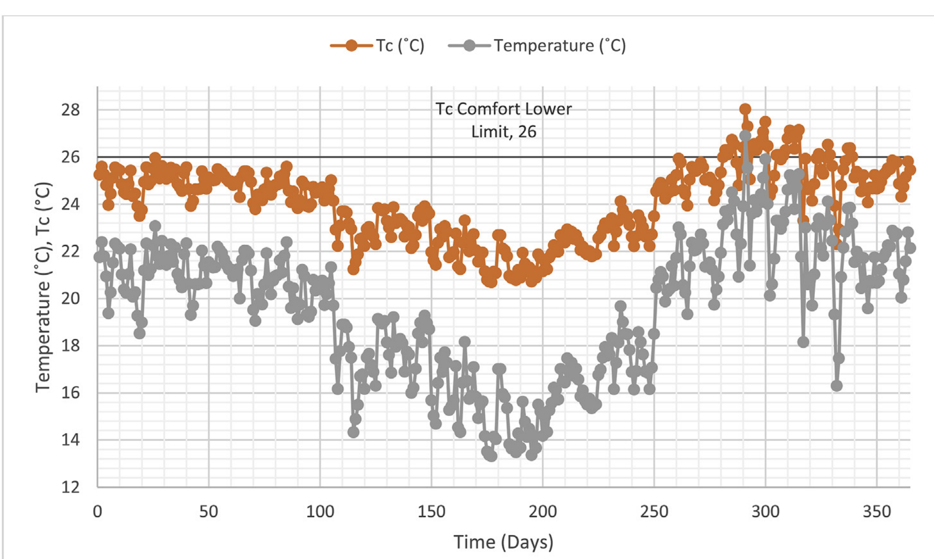

Fig. 2. Average annual patterns of indoor thermal discomfort at UZ.

Table 3
The mean number of days in each month with their respective outdoor discomfort conditions.

Month	THI > 26	26 > THI > 24	24 > THI > 21	21 > THI > 15	THI < 15
January	0	0	1	30	0
February	0	0	0	28	0
March	0	0	0	31	0
April	0	0	0	29	1
May	0	0	0	29	2
June	0	0	0	14	16
July	0	0	0	2	29
August	0	0	0	18	13
September	0	0	0	29	1
October	0	0	11	20	0
November	0	0	9	21	0
December	0	0	4	27	0
Total	0	0	25	278	62

Students were under cold stress in the morning only in post-rain season and none of the subjects were under cold stress in the rainy and hot seasons. This is a consequence of the general decrease in number of cold hours from 14 h in the cool season to nil in the hot and rainy season without cold stress conditions. Between 10am and 8pm in the cool season 50% of the subjects felt comfortable with the thermal conditions, with cold stress the rest of the day. As for the post-rain season, for the most part 50% of the subjects felt comfortable, but under cold stress between 1am and 8am. In the rain season, the students felt comfortable between 10am and 1pm, and then 50% of the subjects were comfortable the rest of the day. The hot season had the maximum values of THI, with 100% of the students feeling comfortable between 10am and 7pm, the rest of the day 50% of the subjects felt comfortable (Fig. 5).

3.8. Average diurnal variation of seasonal indoor thermal comfort

All diurnal variations of indoor thermal comfort for the seasons have a minimum between 5 a.m. and 7am, a maximum at around 3pm in the afternoon, and no heat stress conditions throughout the day (Fig. 6). The hot season is the only one with comfort conditions between 12pm and 6pm, whilst the rest of the days and seasons were under cold stress. The slope of the curve is steeper between 7 a.m. and 3pm when the comfort levels are rising than then after when they decrease in time. This suggests that heat gain during the day is at a faster rate than heat loss from night to early hours of the next day. The cooling rate over night is faster in the cool than in other seasons.

Table 4
Days of the month with their respective indoor discomfort conditions.

Month	Tc > 32.5	32.5 > Tc > 26	Tc < 26
January	0	0	31
February	0	0	31
March	0	0	31
April	0	0	31
May	0	0	31
June	0	0	31
July	0	0	31
August	0	0	31
September	0	0	31
October	0	16	15
November	0	12	18
December	0	3	28
Total	0	31	334

3.9. Percentage hourly frequency of occurrence of outdoor comfort conditions in each season

According to Fig. 7, on average in the cool season, 58% of the day was under cold stress, and the rest of the days under 50% comfort conditions. Comfort conditions took 33% and 25% of the day in the hot season and rain season respectively, and a day in the post-rain season with 29% under cold stress, and 50% of the subjects feeling comfortable the rest of the day. The chances that 50% of the people at the university

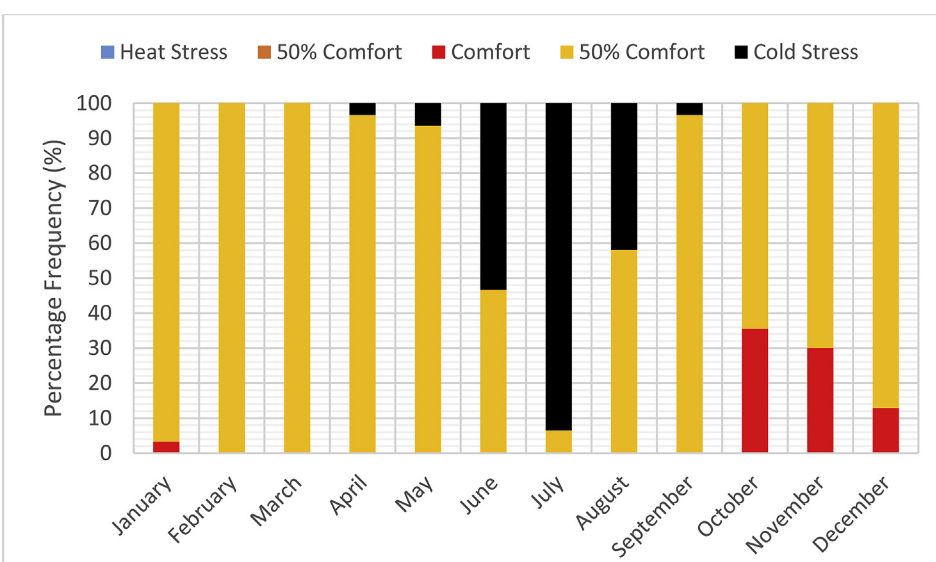

Fig. 3. Average percentage occurrence of outdoor discomfort days in each month.

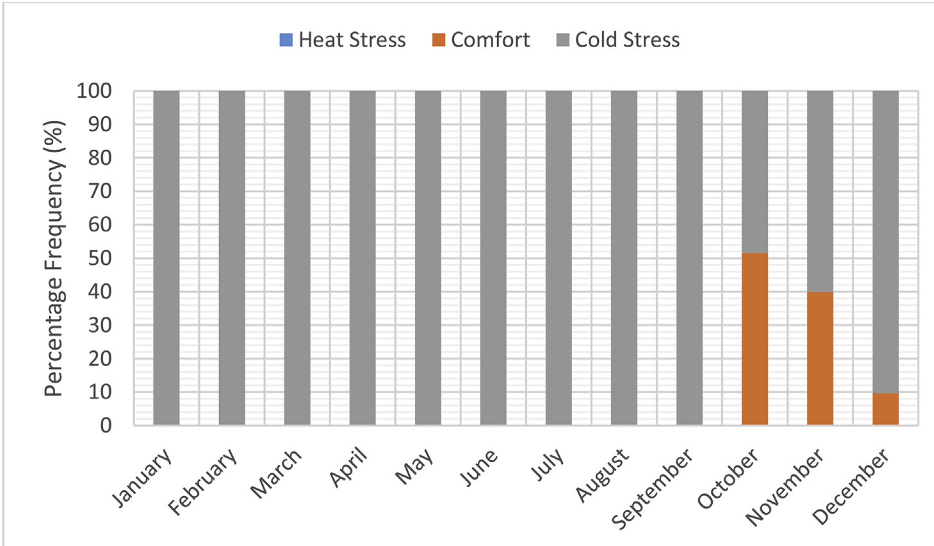

Fig. 4. Average percentage occurrence of indoor discomfort days in each month.

would feel comfortable outdoors are higher in the cool seasons. The proportion of events of perfectly comfortable conditions (where everyone would feel comfortable outdoors) where highest in the hot season. The hot season and the rainy season where the most heat-stress free due to no record of heat or cold stress events during the study period.

3.10. Percentage hourly frequency of occurrence of indoor comfort conditions in each season

Fig. 8 shows that a day spent indoors in the hot season, 25% of the day was under comfort conditions, whilst the rest of the day and all the other seasons were under cold stress. The result indicates that during both day and night in the hot season there were no events of heat stress recorded. The university is generally cool indoors as shown by high proportion of cold stress hours in all the seasons.

3.11. Range of comfort conditions for observed temperature and relative humidity patterns

From the range of recorded relative humidity and temperatures, Fig. 9, shows the range of environmental conditions in which at least 50% of subjects felt comfortable outdoors at UZ, bounded by the maximum recorded relative humidity, the minimum recorded relative humidity, and the THI at 24 and THI at 15 curves. The range of temperature at which at least 50% could feel comfortable became narrow as the relative humidity increased. At relative humidity above 93% people at the university would continue to feel mostly comfortable provided the outdoor air temperature ranges between 15 and 24 °C. Outdoor discomfort level can be held constant by decreasing temperature while increasing relative humidity.

4. Discussion of findings

This study employed simple and parsimonious indices for indoor and outdoor thermal discomfort analysis at a tertiary learning institution. The results showed that there are more uncomfortable daily

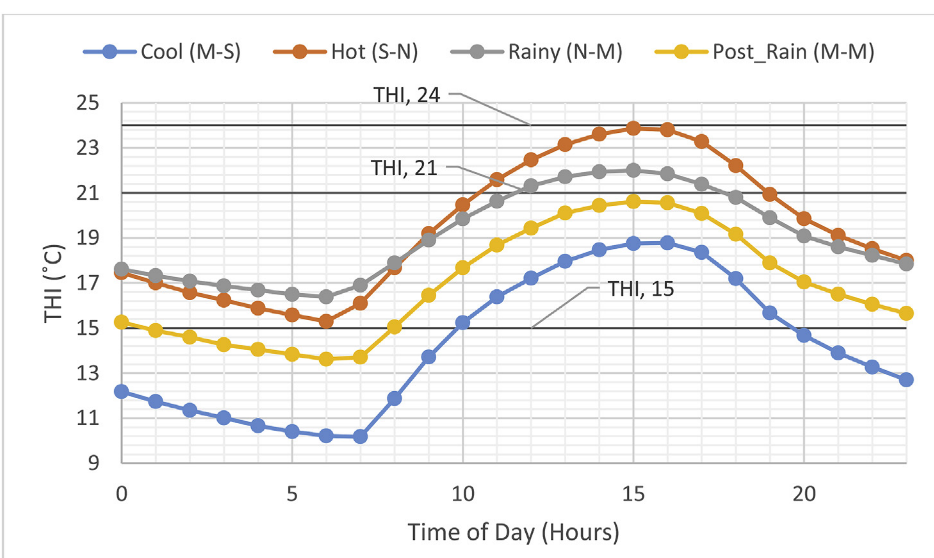

Fig. 5. Diurnal variation of seasonal outdoor thermal discomfort at UZ.

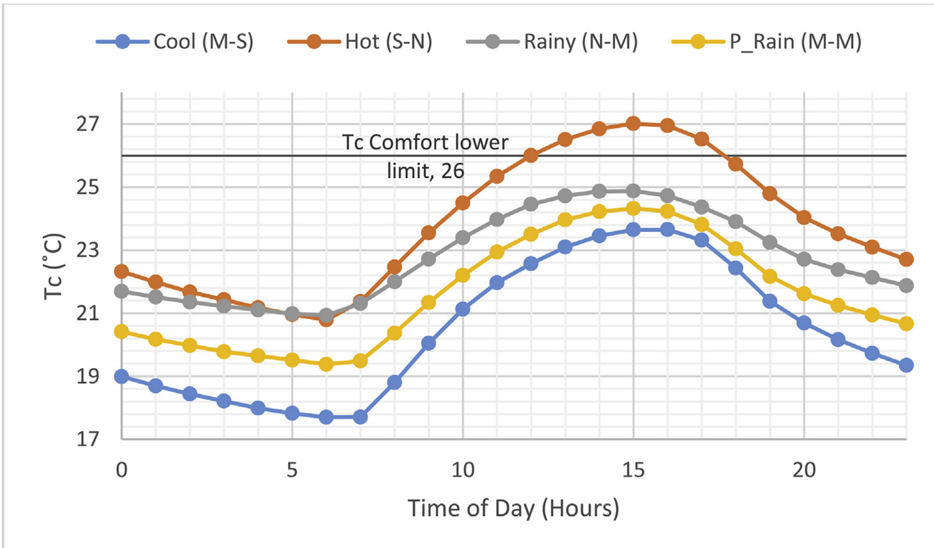

Fig. 6. Diurnal variation of seasonal indoor thermal discomfort at UZ.

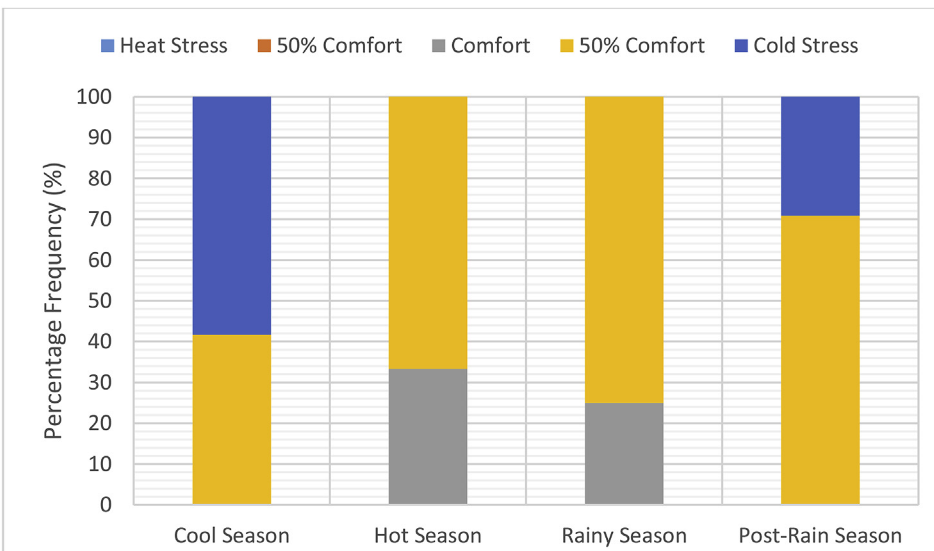

Fig. 7. Percentage hourly frequency of occurrence of outdoor discomfort conditions in each season.

temperature averages biased towards cold than hot conditions in all seasons outdoors. The large amount of vegetation cover in the study area contributed to the observed uncomfortable hours as they provided shade, evapotranspiration, and increasing latent heat transfer thereby increasing the cooling effect (Cao et al., 2008; Puliafito et al., 2013). Since vegetation growth is at its peak during the hottest times of the year (hot, rain and pot-rain seasons), the cooling effect would reduce the peak of temperatures (Torrance, 1981; Unganai, 1996) which would have otherwise been recorded if there had been no vegetation. The heat moderation effect of vegetation also explains why heat stress was not recorded even during the hot season for the entire study period. This concurs with Puliafito et al. (2013) who observed that areas with bio-climatic components such as vegetation are low temperature zones. Landscape morphology was also found to strongly influence temperature in Putrajaya Malaysia (Syed Othman Thani et al., 2013). The wind in the study area is also known to be strongest at end of cold season and beginning of hot season during which highest temperatures are recorded (Torrance, 1981), which further counters the otherwise peak temperatures which could have been recorded.

During the hot and rainy seasons temperature and DI were found to inversely relate with relative humidity. This implies that increasing the temperature while decreasing the humidity led to increase in outdoor discomfort. Reduction in humidity in the face of high temperatures lowered the cooling effect of evaporation thereby increasing adverse effect of heating on human physiology. An inverse relationship between RH and air temperature was also observed in Mossoso Brazil (Azevedo et al., 2015). In Brazil, urban areas were characterised by high temperature, low RH and uncomfortable thermal conditions when compared to nearby rural areas in both the wet and dry season. A combination of high temperature and RH, therefore, subjects population to uncomfortable conditions. In the cool and post rain seasons DI was positively related to both temperature and RH. As a result, cold stress was at its peak when both temperature and RH were low. The cold stress was associated to low temperatures and influx of cold air which characterize the cool season in Zimbabwe (Kamusoko et al., 2013; Torrance, 1981).

The diurnal variation of both indoor and outdoor comfort show minimum THI and Tc values for all seasons observed early morning (6am and 7am), and the maximum values for both indoor and outdoor diurnal variations being recorded around 3pm for all seasons. During

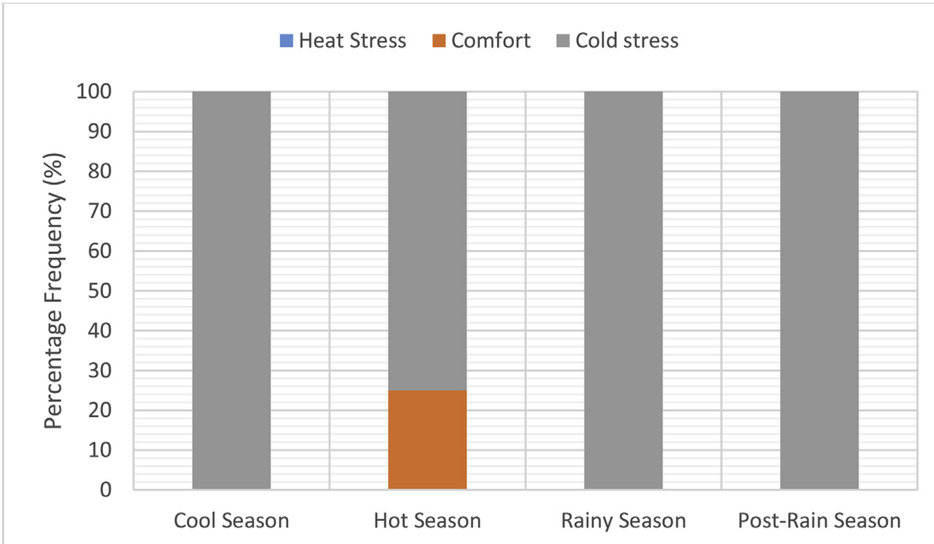

Fig. 8. Percentage hourly frequency of occurrence of indoor discomfort conditions in each season.

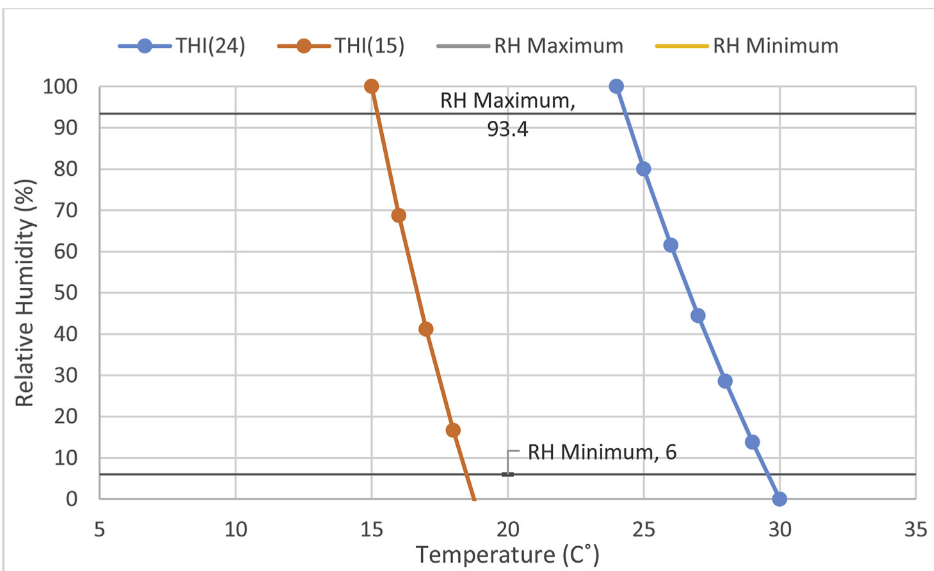

Fig. 9. Range of comfort conditions for observed temperature and relative humidity patterns.

the day, solar heating over lands surface increases the temperature and moisture. The temperatures then gradually decrease over night until the early hours of the next day. This concurs with the notion that radiative cooling of the land surface at night enhances atmospheric stability, suppressing convection and leading to minimum temperatures in the early morning (Yang and Slingo, 2001). The overnight cooling was faster in winter than in other seasons. Although not measured in this study, strong winds in Zimbabwe are encountered mostly in the cool season which speed up heat removal. The cool season in Zimbabwe is dry with large events of clear skies (Torrance, 1981) which promote radiative heat loss to outer space thus speeding up heat loss at night.

For both indoors and outdoors the hot season was observed to be most thermally comfortable between 12pm and 6pm. On average, the overall temperatures at the institute are biased towards the cold stress regions, therefore the warmer it is the more comfortable it will be. Since the hot season has the highest amount of insolation received, buildings have a higher tendency of warming up in this season leading to more comfortable indoor environments. Madhumathi (2012) expressed that the heat absorbed by building when exposed to solar radiation increases thermal level indoors and sometimes even to stressful level. The range of humidity values in the hot season were within the comfortable region recommended by ASHRAE (20%–70%) (KNMI, 2000). Outdoors, the hot and rainy sub-seasons are more thermally comfortable than the post-rain and cool sub-seasons because the hot and post-rain sub-seasons comprise the summer season in which the highest amount of insolation is received (Mushore et al., 2018). For indoor conditions, the hot season is more thermally perfectly comfortable days than other seasons in turn. The high outdoor temperature during this part of the year raises indoor temperatures to comfortable levels even in the absence of air conditioning.

For outdoor conditions, the cold season was observed to be the least thermally comfortable with partial comfort (at least 50% of students feeling comfortable) for a few hours when insolation is at its peak in the afternoon. The low levels of comfort were also recorded indoor during the cold season where cold stress was recorded throughout an average day. The least amount of insolation is received in this season implying that there will not be enough heat to warm the insides of buildings so subjects felt discomfort or under cold stress. Although not measured in this study, the pressure systems during the cold season are known to drive cool southerly air into Zimbabwe (Torrance, 1981). The cool air

flow is superimposed on low insolation level due to northward migration of the sun to reduce the temperatures during the cold season. Similar to our finding, Cheng et al. (2010) also stressed that temperature, wind speed and solar radiation are the most influential factors in determining human thermal sensation.

During the rainy, post-rainy and cool season none of the subjects felt comfortable indoors, they were under cold stress. Although there is partial outdoor thermal comfort (50% of the subjects felt comfortable) in the rainy season throughout the whole day, the insolation was not enough to warm the free running buildings. Partial comfort outdoors recorded in the rainy season could be explained by alternating hot and cool to mild conditions during that season. During rainy episodes temperatures drop due to cooling effect of rain water as well as due to reduction in insolation in the presence of high amount of cloud cover (Torrance, 1981). On clear skies large amount of insolation is received resulting in increased comfort within the same season. While large amount of insolation is received when skies are clear in the rainy season, partial comfort could also relate to lowering of temperatures due to evaporation cooling from wet ground (high water table) and abundant healthy vegetation. The same reasons can also explain partial outdoor comfort experienced during the post-rain season. The water table will still be generally high and vegetation healthy due to water received in the rainy season.

Generally, the discomfort levels at the University of Zimbabwe were biased towards cold stress as they mostly ranged between partial comfort and cold stress both indoors and outdoors. The university is located in a low density residential area where temperatures were found to be lower than in other parts of the city due to cooling associated with low built-up fraction and abundance of well-maintained vegetation (Mushore et al., 2016, 2018). Increasing greenery cover in an area was found to improve thermal comfort in Shanghai (Yang et al., 2011). Location was also found to be an important determinant of indoor and outdoor thermal discomfort (Ormandy and Ezratty, 2016). The combined effect of location and land cover was also observed in Athens during a heat wave where discomfort levels were higher in downtown and industrial areas than in suburbs and mountains (Polydoros and Cartalis, 2014). During this heat wave in Athens DI levels lower than 27 °C where recorded which indicated partial comfort in vegetated rural and mountainous areas while others areas recorded heat stress.

5. Recommendations

The study recommends that:

- future studies should investigate the link between thermal discomfort an socio-economic pressures such demand for water and air-conditioning energy
- Instead of using thermal indices determined using the response of subjects in other parts of the world in reaction to thermal properties under atmospheric conditions which are not exactly the same as in the area of interest, further studies should determine their own indices which are relevant to their area of interest.
- For improved accuracy of thermal studies, indices which include a higher number of psychological, physiological and climatic variables should be used.
- Future studies should consider analysis over a longer period of time and this implies the need for continued measurements at the University of Zimbabwe and other universities and learning institutions.

6. Conclusions

Indoor and outdoor human thermal comfort at the University of Zimbabwe was assessed applying standard indices on in-situ temperature and humidity data from an automatic weather station. In view of the findings, the study concluded that temperatures are below the threshold values considered as comfortable for the majority of the subjects at UZ, and biased towards the cold regions. On average, the hot season was the most thermally comfortable season throughout the whole year and in a diurnal cycle, it is more comfortable for students both indoors and outdoors in the afternoon. There were no significant cases of heat stress recorded during the period under study. Therefore, UZ is highly comfortable for both indoor and outdoor activities during the hot season. The study expresses the value of considering human thermal comfort implications when designing buildings, at work places and learning institutions as well as when deciding locations and timing of indoor and outdoor activities. The study also ascertains the value of strengthening enforcement of policies around maintenance of urban greenery as they play a crucial role in moderating thermal comfort levels both indoors and outdoors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2019.01.010.

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